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Numerical Investigation into the Performance of a Rarefaction Shock Wave Cutter for Offshore Oil-Gas Platform Removal

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NUMERICAL INVESTIGATION INTO THE PERFORMANCE OF A RAREFACTION SHOCK WAVE CUTTER FOR OFFSHORE OIL-GAS PLATFORM REMOVAL

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Abstract. The phase change in iron at 13 GPa results in the formation of rarefaction shock waves upon release. The interaction of multiple rarefaction shock waves induces high tensile stresses within a narrow zone, causing smooth spall. This effect can be exploited to sever cylindrical cross-section pipes, such as those supporting decommissioned offshore oil and gas platforms, using a minimal amount of explosive. Consequently, costs can be reduced and environmental impact minimized. We discuss the numerical techniques used to simulate rarefaction shock waves and the damage to steel resulting from the interaction of multiple rarefaction shock waves.

INTRODUCTION

Motivation

Over 3000 platforms populate the U.S. federal outer continental shelf[1] and more than 100 are removed every year. Complete removal requires that the seabed be left clear, thus, the platform supports must be cut at or below the seabed. Compared with submarine cutting, explosives, are cheaper and less risky. The primary problems associated with explosives concern environmental impact. One strategy for mitigating harm to adjacent sea life is to use special techniques to reduce the amount of explosive required and to place the explosive *inside* the hollow supports of the platform.

In this work we investigate the operation of an explosive device which exploits the phase change in iron at 13 GPa to produce rarefaction shock waves (RSWs) upon release. The interaction of the RSWs induces high tensile stresses within a narrow zone, severing the cylindrical cross-section supports. Using this approach the amount of explosive required and the environmental impact may be reduced.

Rarefaction Shock Waves

The subject of phase transitions and their influence upon shock propagation is discussed in detail by [2]. One consequence of phase transitions is the possibility of rarefaction shock waves. Changes in crystalline form are often referred to as polymorphic transformations. One such example is the $\alpha-\varepsilon$ transition in iron which occurs at approximately 13 GPa. This transformation in iron is discussed in detail by Giles et al. [3] and Duvall and Graham [4].

Figure 1 shows the Hugoniot for iron with the phase transition from α to ε commencing at point A. When iron is compressed beyond the point A, the lattice begins to rearrange itself with smaller equilibrium interatomic distances (ε phase). Consequently, decreasing the volume in the phase transition region (between point A and B in Figure 1) requires a much smaller increase in pressure than for pressures below P_a (α phase). In the region A-B the material is in a two-phase state and beyond point B the transformation from state α to state ε is complete. Figure 3 shows the speed of sound in iron in the region of the phase transition. The relative ease of compression in the region A-B results in the possibility of rarefaction shocks.

Figure 2a depicts qualitatively the evolution of a simple right-going rarefaction wave in iron. In this case the C_+ characteristics are straight lines of slope $dx/dt = u+c$ (where $u = -\int c d\rho/\rho + const$ is the particle velocity and c is the speed of sound). The speed of sound of iron in the region of the phase transition is discontinuous, with lower sound speed between A and B (see Figure 3). As a result, characteristics from points with pressures below p_A (such as point C) overtake characteristics with pressures between p_A and p_B (such as point

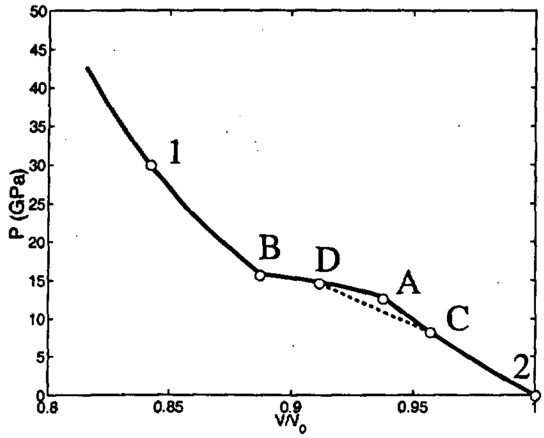

FIGURE 1. Hugoniot curve for iron in the region of phase transition.

D). This results in an immediate steepening of the rarefaction wave at point *A*. The jump ceases to grow when the upper pressure reaches p_B because the sound-speed at *B* exceeds that of lower pressures. The final, steady rarefaction wave structure resembles that of Figure 2b and includes a steep jump: the rarefaction shock-wave (RSW).

In the absence of RSWs, spall results in rough surfaces due to micro inhomogeneities in the tensile stress region. However, where two RSWs meet, a very narrow region of large tension occurs and "smooth" spall can result. This "smooth" spall has been observed experimentally by numerous authors[5, 6, 7].

SIMULATING RAREFACTION SHOCK WAVES

We chose to use Century Dynamics' Autodyn software to simulate rarefaction shock waves in iron. Before Autodyn could be applied to this problem, two key aspects of RSWs were addressed:

- The anomalous equation of state which allows RSWs
- Appropriate treatment of tensile shocks

The shock-wave velocity (u_s) is shown as a function of particle velocity (u_p) in Figure 4. This relationship is readily incorporated into a shock equation of state. The resulting pressure as a function of relative volume is shown in Figure 1.

Most hydrocodes are developed with only compressive shocks in mind. Consequently, the simulation of RSWs can require some improvements to avoid excessive "ringing" in the wake of the shock. The standard version of Autodyn has viscosity only enabled for compression. Century Dynamics graciously provided us with a version of Autodyn with viscosity enabled for tensile shocks. A comparison of simulations performed with the standard and updated version of Autodyn are shown in Figure 5.

RSW CUTTER

The rarefaction shock-wave (RSW) cutter test device developed at VNIIEF is described by Figure 6. The device consisted of a ring of explosive supported on a disk which was lowered down the center of the pipe. The pipe in the test had an outer radius of 762 mm and thickness of 50 mm. The initiation points were distributed at regular intervals along the top and bottom of the inner surface of the explosive ring. The mode of operation of the device is explained in the following section.

RESULTS

Autodyn was used to simulate the operation of the RSW in 2 dimensions. Figure 7 shows the evolution of the pressure field. The two point initiation drives two shock waves into the iron which meet on the axis of symmetry. The peak pressure in the iron well exceeds the transition pressure, so the release of the two shock waves produce two RSWs. Where these RSWs intersect with the centerline, smooth spall is predicted to result. Beyond a depth of approximately 25 mm into the iron the peak pressure no longer exceeds 13 GPa and no RSW occurs upon release. However, the combined shock-wave resulting from the merging on the centerline travels out through the iron and is mostly reflected at the iron-sand interface. The returning release wave well exceeds the spall strength of iron and is predicted to cause a large region of rough spall. Figure 7 shows the failed regions highlighted.

The results from an experiment by VNIIEF are shown in Figure 8. A narrow band of smooth spall is evident adjacent to the pipe interior, similar to that observed in the simulation. However, the smooth spall region in the experiment appears to occur immediately adjacent to the inner surface of the pipe (unlike the simulation where it was seen several millimeters inside the pipe wall. The pipe recovered from the test shows an extensive region of rough spall near the pipe exterior, consistent with the simulation.

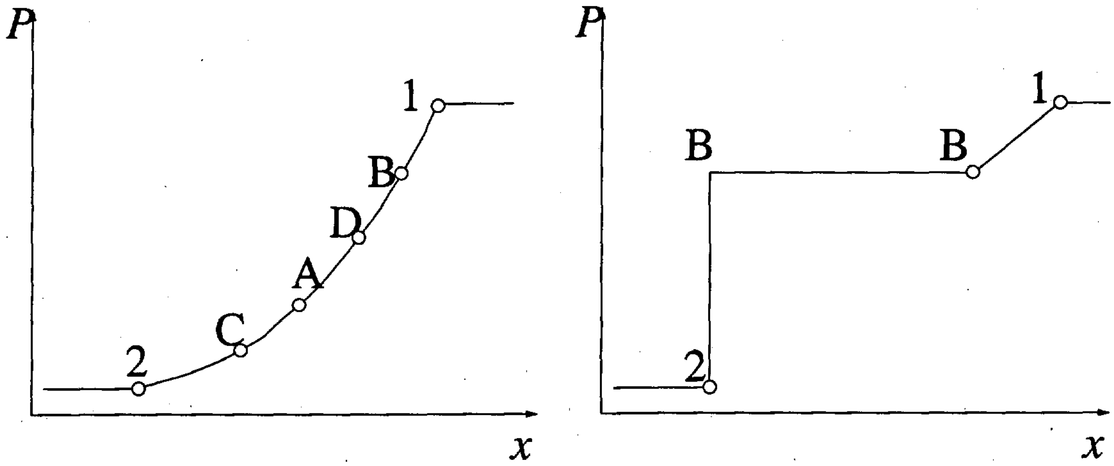

FIGURE 2. (a) A simple right-going rarefaction wave and (b) the character of the final pressure distribution with rarefaction shock.

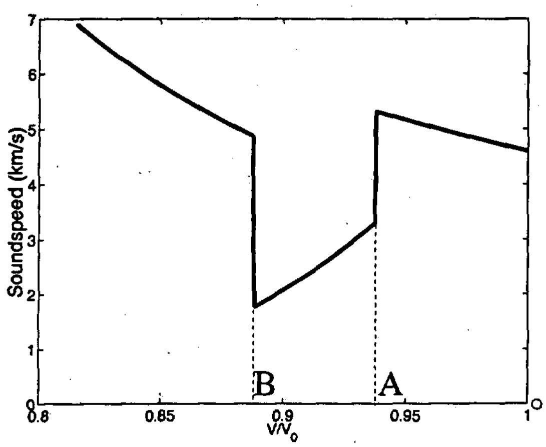

FIGURE 3. Sound-speed for iron in the region of phase transition.

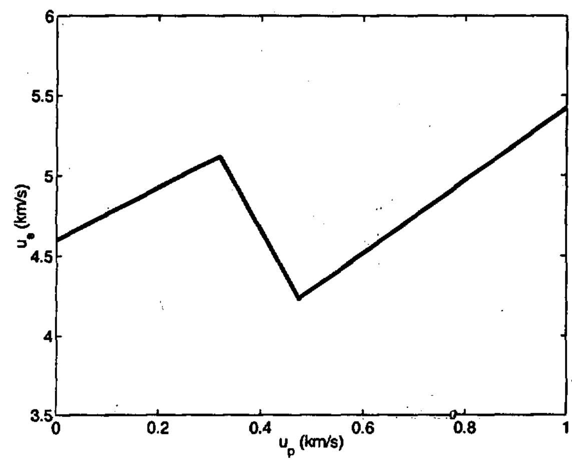

FIGURE 4. Shock-wave velocity (u_s) versus particle velocity (u_p) for iron.

DISCUSSION

We have demonstrated that the key features of a rarefaction shock-wave (RSW) can be simulated by a modified version of Autodyn using a shock equation of state. Our simulations of the RSW cutter device indicate a region of potential smooth spall which corresponds well with that observed experimentally. We are in the process of exploring different damage models to simulate the propagation of the crack formed by the smooth spall. At this point, the simulations do not conclusively indicate that the smooth spall is necessary to ensure failure of the pipe.

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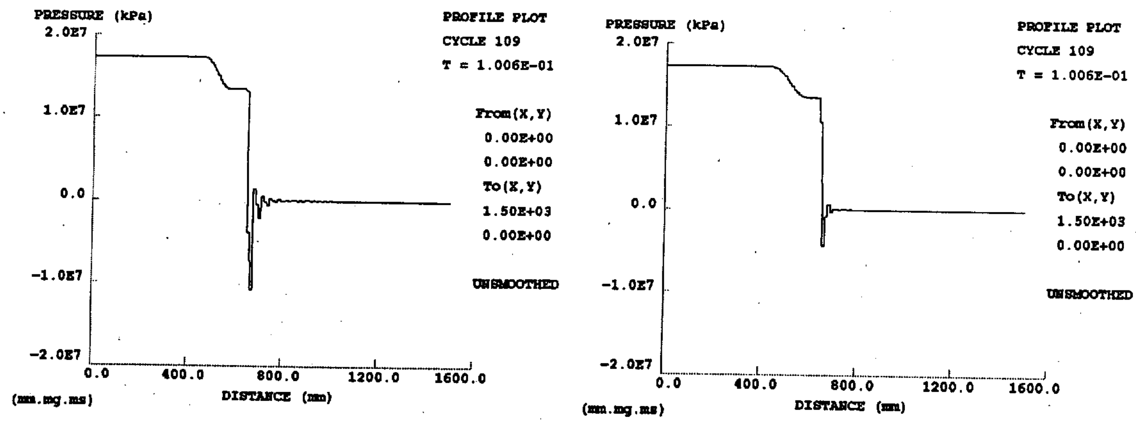

FIGURE 5. Comparison of propagation of RSW with (a) standard Autodyn and with (b) Autodyn modified to include artificial viscosity in regions of tension. The initial conditions were a 1000 mm bar of iron compressed to approximately 17 GPa, released at the ends.

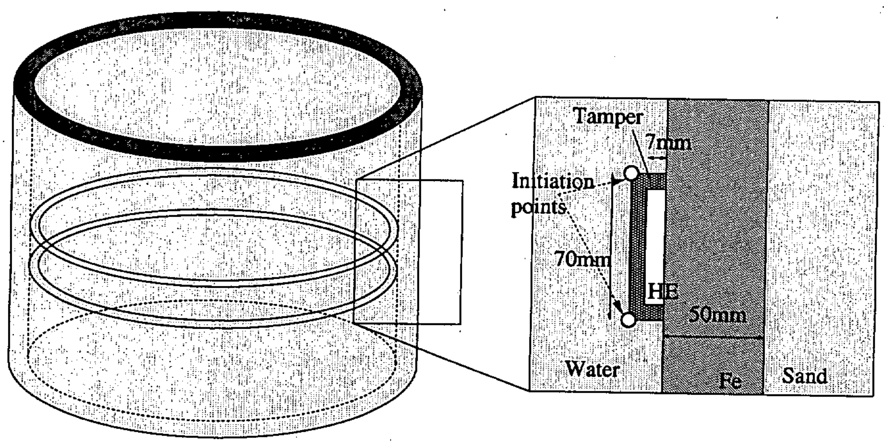

FIGURE 6. Depiction of test setup and RSW cutter.

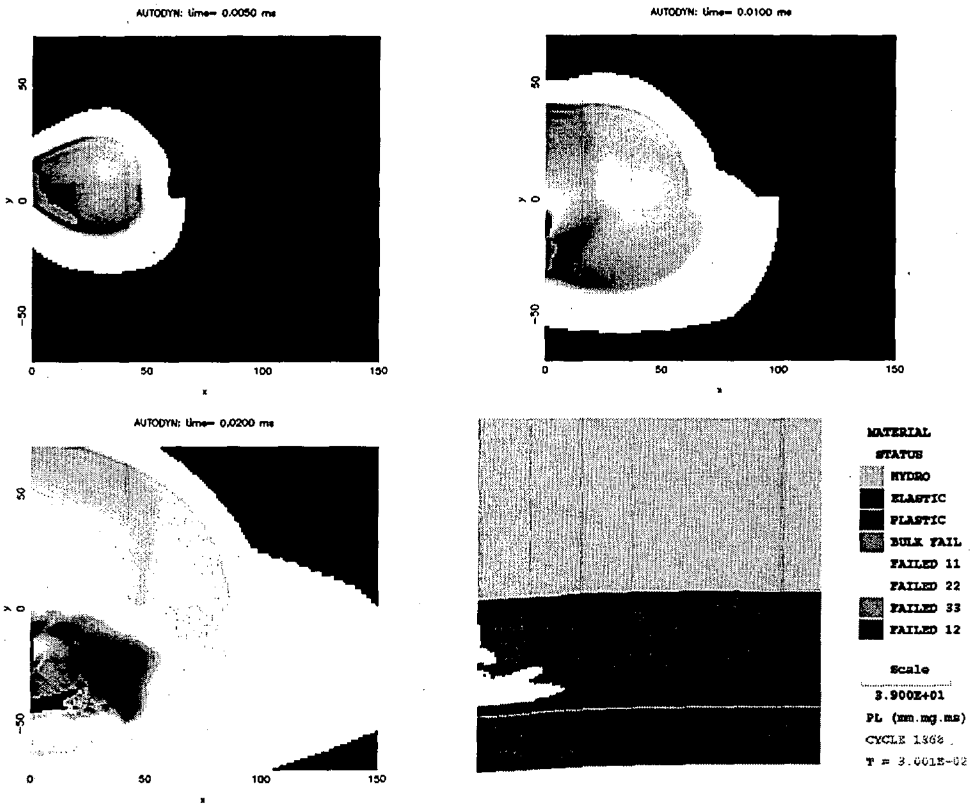

FIGURE 7. The simulation of the RSW device using Autodyn. In the final frame, the failed regions are highlighted.

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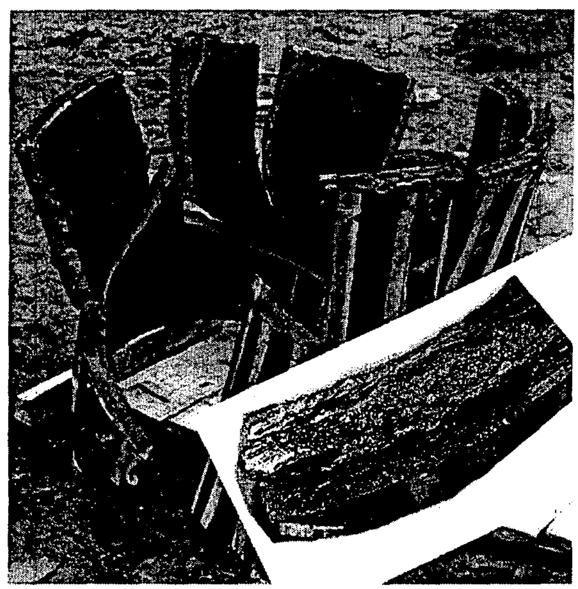

FIGURE 8. The result of a test of the RSW concept, performed by VNIIEF. A narrow band of smooth spall is evident adjacent to the pipe interior.

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